REMARKS/ARGUMENTS

Favorable reconsideration of this application as presently amended and in light of the following discussion is respectfully requested.

Claims 1-8 are presently active. Claims 2 and 6-8 have been presently amended.

In the outstanding Office Action, Figures 10A and 10B were objected to for not having a legend such as --Prior Art--. Claims 6, 7, and 8 were objected to due to informalities. Claim 8 was rejected under 35 U.S.C. § 102(e) as being anticipated by Nishihara et al (U.S. Pat. No. 6,734,763). Claim 2 was rejected under 35 U.S.C. § 103(a) as being unpatentable over Whatmore et al (U.S. Pat. No. 6,774,746) in view of Barber (U.S. Pat. No. 6,601,276). Claims 5-7 were rejected under 35 U.S.C. § 103(a) as being unpatentable over Whatmore et al and Barber further in view of Barber et al (U.S. Pat. No. 6,657,517) or Nishihara et al and Barber et al (U.S. Pat. No. 6,674,291). Claim 4 was objected to for being dependent from a rejected base claim but would be allowable if rewritten in independent form to include the limitations of the base claim and any intervening claims. Claims 1 and 3 were indicated as being allowed.

Regarding the objection to the drawings, on the replacement sheets, Figures 10A and 10B have been labeled with - -Background Art--. Thus, it is respectfully submitted that the objection to the drawings has been overcome.

Regarding the objection to the claims, the claims have been amended to address the informalities. Thus, it is respectfully submitted that the objection to the claims has been overcome.

Next, Applicants acknowledge with appreciation the indication of allowable subject matter in Claim 4 and the indication of allowance for Claims 1 and 3.

Regarding Claim 2, Claim 2 defines a thin-film piezoelectric resonator having an upper electrode and a lower electrode arranged on opposite surfaces of a piezoelectric thin film for applying an excitation voltage to the piezoelectric thin film; and has ground electrodes

arranged on the same plane with at least one of the upper electrode and the lower electrode, and not opposing the upper or lower electrode.

The Office Action asserts that it would have been obvious to modify the ground electrodes disclosed by Whatmore et al with the thicker ground sections disclosed by Barber.[1] However, such a combination would not produce the claimed invention in which the ground electrodes are not opposed to the upper or lower electrodes as neither reference discloses or suggests this feature.

Thus, independent Claims 1, 2, and 3 and the claims dependent therefrom patentably define over the applied references.

Regarding Claim 8, Claim 8 had been amended to recite features not found in Nishihara et al. Claim 8 defines producing, for at least one of the upper electrode and the lower electrode, a resonant region and a lead-out portion extending from the resonant portion. The lead-out portion has an electrode thickness that differs from an electrode thickness of the resonant portion. As seen by the example in Applicants' Figure 1B the lead-out portion 16b for upper electrode 16 has a thickness greater than the resonant region 16a. The central regions and the lead-out regions in Nishihara et al are shown as having the same thickness. Indeed, this feature in Claim 8 is similar to that defined in Claim 1, and similar to that identified in the outstanding Office Action with regard to Claim 1 as allowable subject matter. Therefore, independent Claim 8 is believed to patentably define over the applied references.

Finally, Applicants respectfully request that the PTO 1449 form accompanying the Information Disclosure Statement filed September 26, 2003 be fully initialed and returned with the next office action. The outstanding Office Action returned a partially initialed PTO 1449 form with the reference AV not initialed. The AV reference was supplied to the U.S. Patent and Trademark Office with the filing of the Information Disclosure Statement on September 26,

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[1] Office Action, page 5, lines 21-23.

2003, as indicated by the enclosed date-stamped filing receipt. A courtesy copy of the AV reference is attached.

Consequently, in view of the present amendment and in light of the above discussions, the outstanding grounds for rejection are believed to have been overcome. The application as amended herewith is believed to be in condition for formal allowance. An early and favorable action to that effect is respectfully requested.

Respectfully submitted,

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(OSMMN 08/03)
GJM:RAR:clh

Attachments: Information Disclosure Statement and PTO 1449 filed September 26, 2003
Date Stamped Filing Receipt of September 26, 2003, Courtesy Copy of the AV reference on the PTO 1449 form filed September 26, 2003

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Amendments to the Drawings

The attached sheet of drawing includes changes to Figures 10A and 10B. This sheet, which includes Figures 10A and 10B, replaces the original sheet including Figures 10A and 10B.

Attachment: Replacement Sheet.

mz

OSMM&N File No. 243190US2

Dept.: PP/JF

By: MJS/dlb

Serial No. NEW APPLICATION

In the matter of the Application of: Eiju KOMURO, et al.

For: THIN-FILM PIEZOELECTRIC RESONATOR AND METHOD FOR FABRICATING THE SAME

Due Date: 09/27/03

The following has been received in the U.S. Patent Office on the date stamped hereon:

- 36 pp. Specification 8 Claims/Drawings 9 Sheets and 3 Pages Application Data Sheet
- Utility Patent Application Transmittal
- Credit Card Form for $1,274.00
- Dep. Acct. Order Form
- Fee Transmittal Form
- Information Disclosure Statement
- PTO-1449
- Cited References (4)
- Statement of Relevancy
- White Advance Serial Number Card

Docket No. 243190US2

APR 19 2005

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

IN RE APPLICATION OF: Eiju KOMURO, et al.

SERIAL NO: NEW APPLICATION GAU:

FILED: HEREWITH EXAMINER:

FOR: THIN-FILM PIEZOELECTRIC RESONATOR AND METHOD FOR FABRICATING THE SAME

INFORMATION DISCLOSURE STATEMENT UNDER 37 CFR 1.97

COURTESY COPY

COMMISSIONER FOR PATENTS
ALEXANDRIA, VIRGINIA 22313

SIR:

Applicant(s) wish to disclose the following information.

REFERENCES

■ The applicant(s) wish to make of record the references listed on the attached form PTO-1449. Copies of the listed references are attached, where required, as are either statements of relevancy or any readily available English translations of pertinent portions of any non-English language references.

☐ A check or credit card payment form is attached in the amount required under 37 CFR §1.17(p).

RELATED CASES

☐ Attached is a list of applicant's pending application(s) or issued patent(s) which may be related to the present application. A copy of the patent(s), together with a copy of the claims and drawings of the pending application(s) is attached along with PTO 1449.

☐ A check or credit card payment form is attached in the amount required under 37 CFR §1.17(p).

CERTIFICATION

☐ Each item of information contained in this information disclosure statement was first cited in a communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of this statement.

☐ No item of information contained in this information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application or, to the knowledge of the undersigned, having made reasonable inquiry, was known to any individual designated in 37 CFR §1.56(c) more than three months prior to the filing of this statement.

DEPOSIT ACCOUNT

■ Please charge any additional fees for the papers being filed herewith and for which no check or credit card payment is enclosed herewith, or credit any overpayment to deposit account number 15-0030. A duplicate copy of this sheet is enclosed.

Respectfully submitted,

OBLON, SPIVAK, McCLELLAND,
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Form PTO 1449 (Modified)

U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

LIST OF REFERENCES CITED BY APPLICANT

ATTY DOCKET NO.	SERIAL NO.
243190US2	NEW APPLICATION
APPLICANT	
Eiju KOMURO, et al.	
FILING DATE	GROUP
HEREWITH	

U.S. PATENT DOCUMENTS

EXAMINER INITIAL		DOCUMENT NUMBER	DATE	NAME	CLASS	SUB CLASS	FILING DATE IF APPROPRIATE
	AA	4,320,365	03/16/82	James F. BLACK, et al.			
	AB						
	AC						
	AD						
	AE						
	AF						
	AG						
	AH						
	AI						
	AJ						
	AK						
	AL						
	AM						
	AN						

FOREIGN PATENT DOCUMENTS

		DOCUMENT NUMBER	DATE	COUNTRY	TRANSLATION YES	NO
	AO	2000-278078	10/06/00	Japan		X
	AP	60-189307	09/26/85	Japan		X
	AQ	WO 99/37023	07/22/99	WIPO (with English Abstract)		X
	AR					
	AS					
	AT					
	AU					
	AV					

OTHER REFERENCES (Including Author, Title, Date, Pertinent Pages, etc.)

	AW	Kiyoshi NAKAMURA, et al., "Thin Film Resonators and Filters", International Symposium on Acoustic Wave Devices for Future Mobile Communication Systems, pgs. 93-99
	AX	
	AY	
	AZ	☐ Additional References sheet(s) attached

Examiner	Date Considered

*Examiner: Initial if reference is considered, whether or not citation is in conformance with MPEP 609; Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

COURTESY COPY

FILED WITH APPLICATION

International Symposium on Acoustic Wave Devices for Future Mobile Communication Systems

Monday, 5th March,

-

Wednesday, 7th March, 2001

Keyaki Hall, Chiba University

Sponsored by Chiba University

千葉大学

Thin Film Resonators and Filters

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Abstract

Expanding electrical communication systems demand new acoustic wave devices that can be used in high frequency ranges. The piezoelectric thin film resonator is a candidate for such devices. In this paper the piezoelectric thin film resonators and filters consisting of a piezoelectric film on the quarter-wave multilayers and their characteristics is discussed focusing on the difference of two resonator configurations, the scatter of the resonator properties due to deviation of the each layer thickness, evaluation of acoustic properties of thin films, and device fabrication.

1. Introduction

Elastic wave devices such as bulk acoustic wave (BAW) and surface acoustic wave (SAW) devices have been extensively used as frequency control devices in various electronic and communication systems for many years. However, expanding electrical communication systems demand new acoustic wave devices that can be used in higher frequency ranges.

Although the frequency range of SAW devices has been extended through improvements in fabrication techniques so far, the limitation of fine electrode patterning now poses a serious problem. On the other hand, piezoelectric thin film resonators consisting of a piezoelectric composite film[1-4], which is supported at the edges on a substrate and has two traction-free surfaces, have been investigated as candidates for elastic wave devices operating above 0.5 GHz. However, the piezoelectric thin film tends to buckle due to stress from the substrate and suffers a change of resonance frequency.

In 1965, Newell investigated a piezoelectric resonator using low and high acoustic impedance quarter-wave interlayers, and fabricated a MHz-range piezoelectric resonator consisting of a piezoelectric ceramic plate glued to a few alternately laminated low and high acoustic impedance quarter-wave plates on a substrate[5]. Replacement of the piezoelectric plate and the quarter-wave plates with thin films would make it possible to obtain a very high frequency resonator. A few papers on such resonators have been published recently[6-12].

In this paper the piezoelectric thin film resonator with acoustic multilayers is theoretically analyzed by considering acoustic loss and electrode thickness. The dependence of the resonance and anti-resonance frequencies, the Q-factor, and the effective electromechanical coupling factor on resonator parameters, especially on the total number of multilayers, is discussed[9, 11]. Simulation on the scatter of the resonator properties due to deviation of the each layer thickness of multilayers from a quarter wavelength is also given[9]. Then, some configurations of piezoelectric thin film filters, an evaluation method of acoustic properties of thin films[13], selection of respective layer materials, and device fabrication are described.

2. Resonator Structure

Consider a resonator consisting of a piezoelectric thin film deposited on alternately laminated low and high acoustic impedance quarter-wave layers (multilayers) on a substrate. The resonator configuration theoretically treated so far is such that the uppermost layer of the multilayers, just below the piezoelectric film, is one with the lower acoustic impedance, and the piezoelectric film has a thickness of a half-wavelength at the fundamental resonance frequency. This configuration is termed the $\lambda/2$ mode configuration. Another possible configuration is such that the uppermost layer of the multilayers has the higher acoustic impedance and the piezoelectric film has a thickness of a quarter wavelength at the fundamental resonance frequency. This is designated as the $\lambda/4$ mode configuration. Both the configurations are illustrated in Fig.1, where N is the total layer number of multilayers, Z is the acoustic impedance, and d is the layer thickness. Subscripts p, e, s, l, and h indicate the piezoelectric film, electrodes, substrate and low and high acoustic impedance layers, respectively.

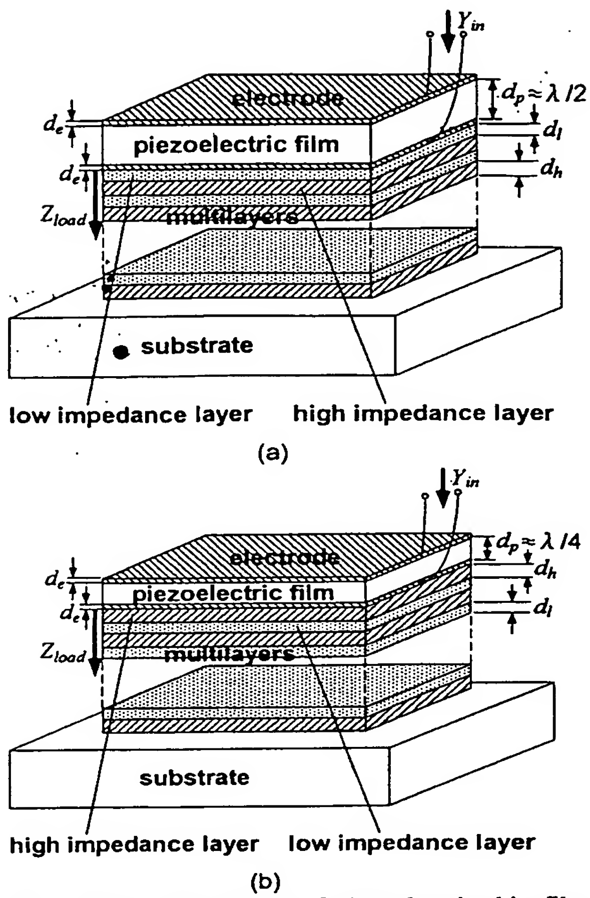


Fig.1. Two configurations of piezoelectric thin film resonators. (a) λ/2 mode configuration. (b) λ/2 mode configuration.

The whole resonator structure including electrodes on both faces of the piezoelectric layer can be represented by a circuit using Mason's equivalent circuits.

In the case of the λ/2 mode configuration, the impedance Z_{load} decreases with increasing N. Thus, the acoustical influence of the substrate on the piezoelectric film can be made sufficiently small using an appropriate number of multilayers and thereby a high-Q thickness mode resonator whose acoustic energy hardly leaks to the substrate is obtained. On the other hand, in the case of the λ/4 mode configuration, the impedance Z_{load} increases with increasing N and the bottom surface of the piezoelectric film can therefore be considered to be almost clamped for large N.

In the theoretical analysis using the equivalent circuit, it is assumed that the piezoelectric film is c-axis oriented ZnO, the electrodes are Al and the substrate is Si. The discussion below will be focused on the representative case which satisfies the condition $Z_lZ_h=Z_p^2$, for convenience in comparing the characteristics of the two configurations. Used parameters are as follows:

K=0.29 (electromechanical coupling factor)
$d_e=0.032\lambda_e$ (λ_e: wavelength in electrodes)
$Z_e=0.5Z_p$, $Z_s=0.6Z_p$
$Q_{mp}=1500$, $Q_{me}=500$, $Q_{ms}=3000$
$Q_{ml}=Q_{mh}=2000$

3. Theoretical Analysis

3.1 λ/2 Mode Configuration

The frequency response of the electrical input admittance Y_{in} of the fundamental thickness mode was calculated for various values of N and Z_h/Z_l. The thickness of each of the multilayers was set equal a quarter wavelength at the antiresonance frequency of the case where the surfaces of the top and bottom electrodes on the piezoelectric film are traction-free (hereafter called 'the traction-free case'). Figure 2 shows the calculated admittance responses for $Z_h/Z_l=3.0$, with N as a parameter. f_0 is the antiresonance frequency of the traction-free case with infinitesimally thin electrodes. The broken curve represents the admittance response of the traction-free case. As can be seen from Fig. 2, the resonance peak and the antiresonance dip of the admittance response become sharp with increasing N. The antiresonance frequency agrees with that of the traction-free case,

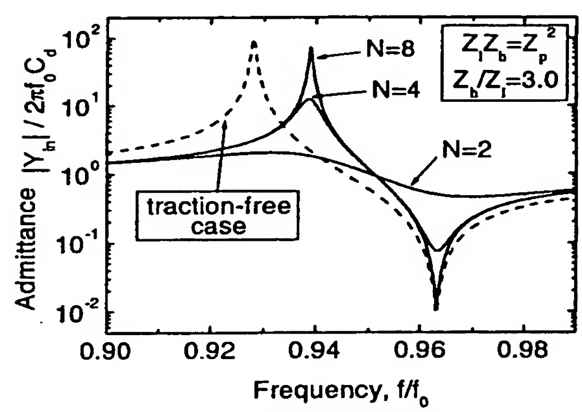


Fig.2. Frequency response of the input admittance for the λ/2 mode configuration.

whereas the resonance frequency is higher than that of the traction-free case even for large N. The reason for this is that the thickness of each of the multilayers is not equal to a quarter wavelength around the resonance frequency.

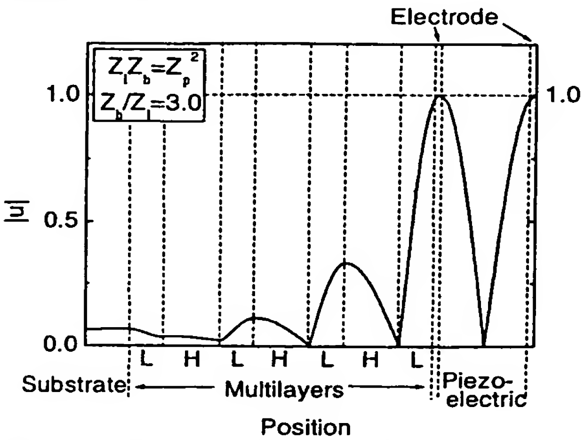


Fig.3. Displacement amplitude distribution at the anti-resonance frequency for the λ/2 mode configuration. N=7.

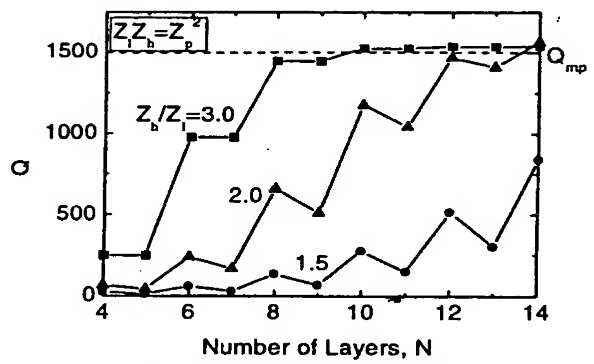


Fig.4. Q vs N for the λ/2 mode configuration.

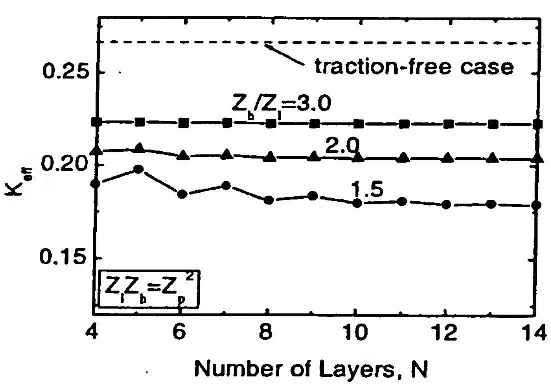


Fig.5. K_{eff} vs N for the λ/2 mode configuration.

The particle displacement in each layer can be calculated using the equivalent circuit. Figure 3 shows the displacement amplitude $|u|$ at the fundamental antiresonance frequency as a function of position for N=7 and Z_h/Z_l=3.0. Both surfaces of the piezoelectric film correspond to the loop of vibration. In the multilayers, $|u|$ decreases with the distance from the piezoelectric film. This indicates that the vibration energy is trapped in the piezoelectric film due to wave reflections at respective boundaries of the multilayers.

Figure 4 shows the electrical quality factor vs layer number N with the impedance ratio Z_h/Z_l as a parameter. The broken line indicates the mechanical quality factor of the piezoelectric film, Q_{mp}. The Q factor finally approaches a certain value with increasing N. Convergence of Q to a saturation value occurs at lower N for large Z_h/Z_l. In Fig.4 the Q factor increases fluctuating with increasing N.

Figure 5 shows the effective electromechanical coupling factor K_{eff} as a function of total layer number N with impedance ratio Z_h/Z_l as a parameter. K_{eff} is somewhat lower than that of the traction-free case. This is related to the disagreement of the admittance response with that of the traction-free case and is attributable to the fact that a part of the vibration energy lies in the multilayers as shown in Fig.3. It should be noted that a large impedance ratio is desirable to obtain a large K_{eff} value.

3.2 λ/4 Mode Configuration

Figure 6 shows the calculated admittance response for the λ/4 mode configuration with Z_h/Z_l=3.0. The broken curve represents the admittance response for the one-side clamped case, where the upper sur-

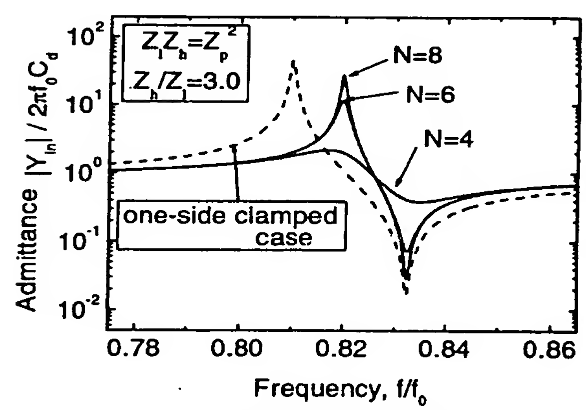


Fig.6. Frequency response of the input admittance for the λ/4 mode configuration.

face of the top electrode is free and the lower surface of the bottom electrode is clamped. f_0 is the antiresonance frequency of the one-side clamped case.

Figure 7 shows the displacement amplitude $|u|$ at the fundamental antiresonance frequency as a function of position for N=7 and Z_h/Z_l=3.0. In the piezoelectric film, a standing wave is set up, whose quarter wavelength is nearly equal to the piezoelectric film thickness.

Figure 8 shows K_{eff} as a function of N. The broken line represents K_{eff} for the one-side clamped case. K_{eff} is slightly lower than that of the λ/2 mode configuration. This is attributable to the facts that the ratio of the energy in the piezoelectric film to the total energy is smaller than that of the λ/2 mode configuration

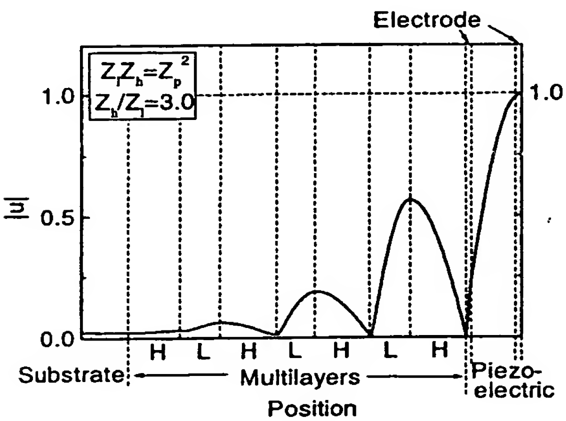


Fig.7. Displacement amplitude distribution at the antiresonance frequency for the λ/4 mode configuration.

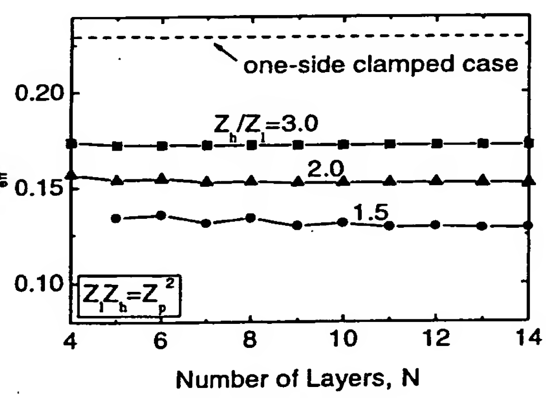
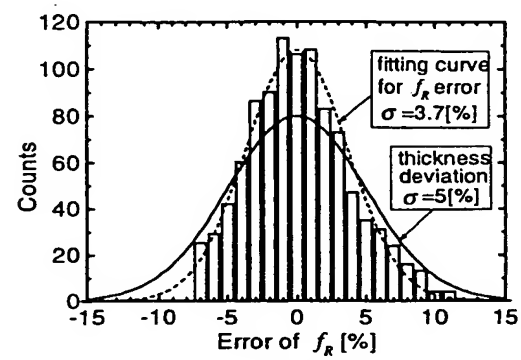


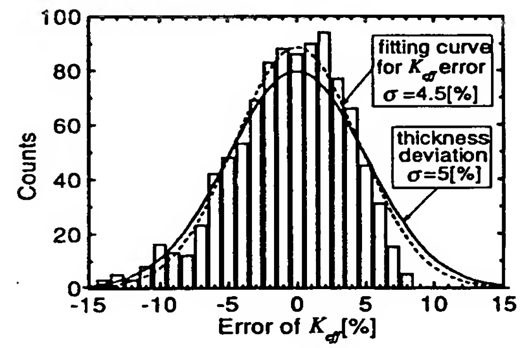
Fig.8. K_{eff} vs N for the λ/4 mode configuration.

4. Scatter of Resonator Properties

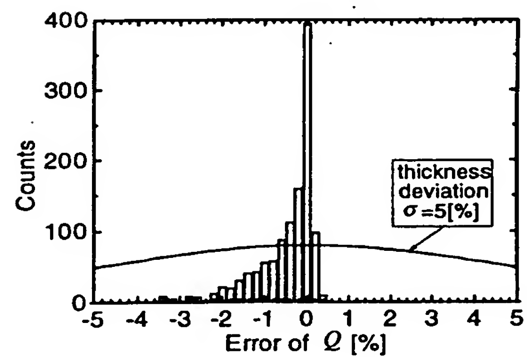
In practical fabrication of the resonators it is difficult to make each layer thickness of multilayers exactly equal to a quarter wavelength. It is important to examine the influence of the layer thickness deviation on the resonator properties. We tried to simulate



(a) f_R



(b) K_{eff}



(c) Q

Fig.9. Distributions of the errors of resonant properties. Z_f=0.4Z_p, Z_h=1.2Z_p, Q_{ml}=Q_{mh}=2000.

the scatter of the resonance frequency f_R, effective electromechanical coupling factor K_{eff} and electrical quality factor Q due to deviation of the each layer thickness of multilayers from a quarter wavelength, assuming that the respective layer thickness deviates randomly and independently with a Gaussian distribution.

The calculation of the frequency response of the input admittance was repeated a thousand times for the case where the standard deviation of thickness, σ, was 5%. The bar graphs of Fig.9 show the deviation distributions of f_R, K_{eff}, and Q.

For comparison, the distribution of layer thickness deviation is represented with solid lines in Fig. 9. The broken curves are the fitting curves for f_R, K_{eff}, and Q. The standard deviations for f_R and K_{eff} are only a little smaller than that of the layer thickness. In contrast, the distribution of Q has an asymmetric one whose deviation is much smaller than the layer thickness deviation. That is, the thickness deviation hardly degrades the quality factor. This is advantageous from a viewpoint of device fabrication.

5. Piezoelectric Thin Film Filters

High frequency filters may be obtained by electrically connecting or acoustically coupling a number of thin film resonators. Figure 10 shows two configurations of acoustically coupled resonator filters. The structure shown in Fig.10(a) consists of two piezoelectric films coupled through quarter-wave multi-layers. The concept of the filter shown in Fig.12(b) is similar to that of the trapped energy monolithic filter. In Sec. 3 it was assumed that the acoustic wave propagates only in the thickness direction, but in the vicinity of the one-dimensional resonance the wave may propagate in the lateral direction as well. If neglecting energy loss due to wave radiation into the substrate, a sort of dispersion curves similar to those of plate waves may be considered. Hence, an energy-trapping phenomenon would be expected to occur. If we put a number of electrode pairs, they would behave just like the monolithic crystal filter due to their evanescent wave coupling.

6. Acoustic Properties of Thin Films

Selection of materials for quarter-wave layers is important for practical devices. SiO_2, Si, and Al would be suitable as the low acoustic impedance

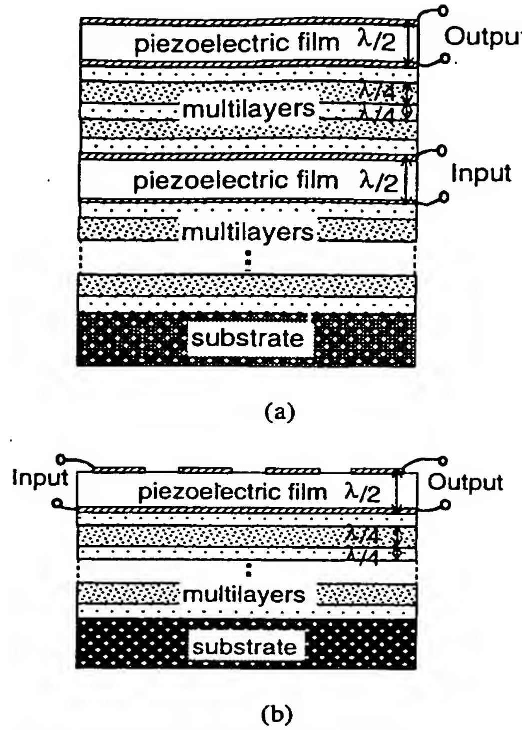


Fig.10. Piezoelectric thin film filters.

material, while Al_2O_3, TiO_2, ZnO, and W as the high impedance material.

The acoustic impedance and phase velocity of a thin film are usually different from those of its bulk material and vary depending on the deposition technique and conditions. Thus, the information about acoustic properties, such as density and elastic stiffness, of the used thin films is necessary to design and fabricate the thin film devices. However, it is not easy to measure the acoustic properties of a thin film less than about 1 μm thick.

We have developed a new simple method for evaluating acoustic properties of thin films[13] from measurement of the resonance frequency change of overtones of a piezoelectric thickness-mode resonator due to deposition of a test film on the resonator surface. When a thin test film is deposited on the surface of a piezoelectric thickness-extensional mode resonator, the resonance frequencies of the fundamental mode and higher overtones would change being influenced by the stiffness c_f as well as the density ρ_f. Therefore, if the film thickness is known, it is possible to evaluate the density and the stiffness of the film simultaneously by measuring the changes of overtone resonance frequencies.

The evaluation process is as follows. The nth overtone resonance frequencies before and after deposition of a film on the resonator, f_n and f_n', are measured for the fundamental and overtone resonance modes, and then they are also calculated using the equivalent circuit for certain values of unknown parameters, ρ_f and c_f. The square errors between measured and calculated values of f_n'/f_n are summed for m modes. The sum is minimized changing the values of ρ_f and c_f, thereby determining the ρ_f and c_f of the test film.

As an example, Fig.11 compares the measured resonance frequencies f_n'/f_n for a 1.28 μm-thick TiO_2 film deposited on a 70 μm-thick Z-cut $LiTaO_3$ thickness-extensional mode resonator with the calculated ones using the evaluated parameters. The resonance frequencies calculated using the evaluated density and stiffness agreed well with the measured values. This suggests that the properties of thin films could be properly evaluated. In Fig.12, the relationship between the evaluated specific acoustic impedance Z_f and longitudinal wave velocity v_f are shown for TiO_2, Al_2O_3, SiO_2, and ZnO films. The former two films were deposited by electron cyclotron resonance (ECR)-assisted electron-beam evaporation using oxygen gas, while the latter two films were grown by RF magnetron sputtering. The acoustic impedance of ZnO is about 2.5 times that of SiO_2, and therefore this combination would be favorable for the acoustic multilayers.

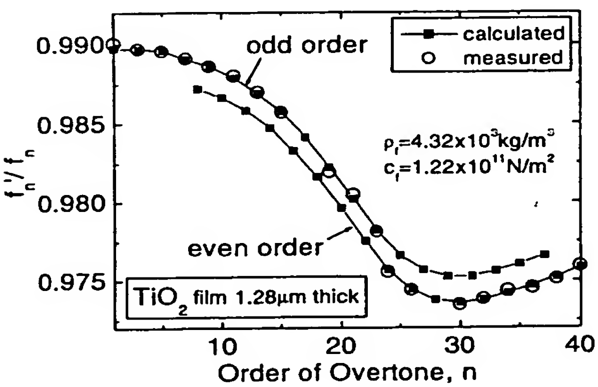


Fig.11. Normalized resonance frequencies, f_n'/f_n, of a piezoelectric plate with a TiO_2 film 1.28μm thick (m=19).

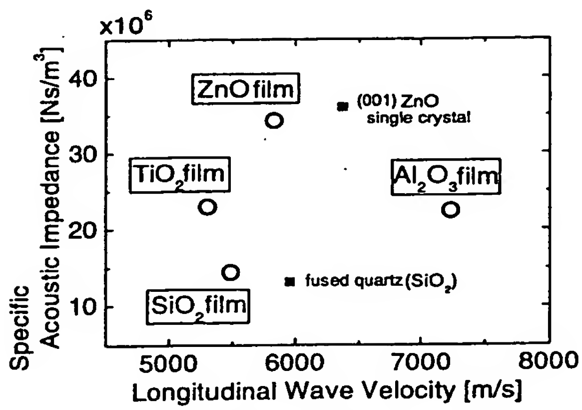


Fig.12. Relation between acoustic longitudinal wave velocity and specific acoustic impedance for thin films.

7. Fabrication

We chose ZnO and SiO_2 as the high and low acoustic impedance quarter wave layers, respectively. This allows us to use only two kinds of films, because ZnO can also be used as the piezoelectric film material. A resonator with five acoustic quarter-wave layers was designed and fabricated on a 70μm-thick Z-cut $LiTaO_3$ substrate. The thickness of ZnO and SiO_2 quarter wave layers was 0.41μm and 0.46μm, respectively, while the $\lambda/2$ piezoelectric ZnO layer was about 0.7μm thick. These films were deposited by a multi-target RF magnetron sputtering system using O_2 and Ar gas. Cr-Au was used as the top and bottom electrodes.

The measured admittance response is shown in Fig.13. The main resonance frequency is about 2.7GHz. Other small resonances appeared with a

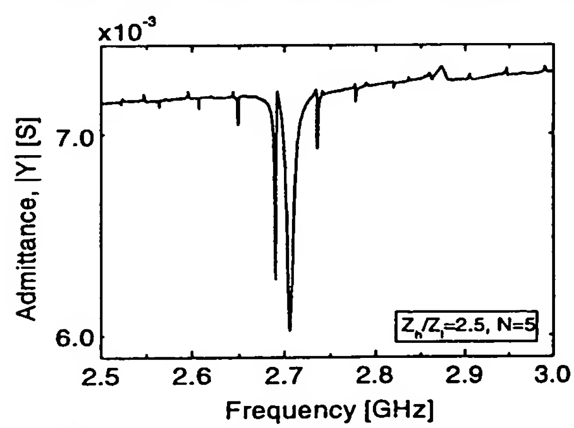


Fig.13. Measured frequency response of a piezoelectric thin film resonator with five $\lambda/4$ multi-layers fabricated on a Z-cut $LiTaO_3$ plate.

period of about 40MHz are the overtones of thickness-extensional modes standing over the whole thickness of the substrate and the thin film resonator. All the spurious resonances can be eliminated by roughening the bottom face of the $LiTaO_3$ substrate.

8. Conclusions

The piezoelectric film resonators and filters with acoustic quarter-wave multilayers have been described focusing on the research of our group. These devices seem promising for use in a very high frequency range from 0.5 to ten some GHz. One of their features is that they have much larger effective coupling factors than those of SAW resonators. The ease of their fabrication would be another feature, if precise control of film thickness can be achieved. Further research has to be done for their practical use.

Acknowledgments

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